JOURNAL OF MATERIALS SCIENCE 31 (1996) 2829–2832

# Influence of the water/cement ratio on the air permeability of concrete

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The durability of concrete structures is mainly affected by the transport of gaseous and liquid substances through its pore system which can potentially cause deterioration of the concrete. Thus, an important indicator of long-term durability is the relative ease with which each aggressive substance is transported through the concrete, in other words, its permeability. Studies were conducted to deepen knowledge of concrete permeability and, in particular, to understand how it is affected by the water–cement ratio, preconditioning temperature and testing pressure. The water–cement ratio is one of the main factors affecting concrete permeability; small changes in this ratio promote large permeability variations. An important increase of air permeability with the water–cement ratio and preconditioning temperature has been noticed. On the other hand, insignificant differences have been observed in the air permeability coefficient at the four testing pressures.

## 1. Introduction

The permeation characteristic of concrete is one of the most important factors affecting the service life of a concrete structure. A relationship between permeability and porosity has been found in hardened cement pastes [1–3] and in concretes [4], and hence, it can be said that aggressive external agents can ingress more or less easily, depending on the pore microstructure.

The porosity of cement paste ranges from 30–40 vol% [5] in the form of either gel or capillary pores which are about $2 \times 10^{-9}$ m and $1 \times 10^{-6}$ m diameter, respectively. Capillary pores are formed as consequence of excess mixing water. The water–cement ratio, therefore, affects this kind of porosity as well as the hydration process and the addition of mineral admixtures. As a consequence, low-permeability concrete may be indirectly achieved by placing maximum limits on the water–cement ratio, and by direct permeability tests which are only performed *in situ* occasionally. In this way, the starting point for the durability requirements for concrete in the European prestandard ENV 206 is to limit the maximum water–cement ratio [6].

At low water–cement ratios, the water-filled space between the cement particles is lower, and then, as the cement hydrates, pores begin to become discontinuous earlier than in higher water–cement ratio pastes. Moreover, there is a limiting water–cement ratio above which complete discontinuity reached cannot be reached. For the cement type used in this research, a limiting water–cement ratio of 0.70 can be assumed. On the other hand, the curing time required to block the capillary pores can be estimated as 3 days, 1 and 2 weeks for water-cement ratios of 0.40, 0.45 and 0.50, respectively [7].

The aim of this work was to study the influence of the water–cement ratio on the air permeability of concrete as a consequence of its influence on the formation of different pore structures.

## 2. Experimental procedure

### 2.1. Materials and mix design

Four water/cement ratios of 0.37, 0.42, 0.47 and 0.52 were chosen to produce the 150 mm diameter × 300 mm concrete specimens made with the mix design showed in Table I. The Portland cement used was a type I according to the European prestandard ENV 197–1 [8]. The 28 day compressive strength was about 30 MPa in 150 mm diameter × 300 mm cylindrical specimens. The specimens were cured at 100% relative humidity for 24 h. Soon after the specimens were preconditioned at 20, 40 and 80 °C in an oven up to constant weight before testing.

### 2.2. Testing procedure

The experimental apparatus to measure air permeability in concretes is described elsewhere [9]. The testing cells were fixed to the specimens leaving a circular passing area. Thereafter, an inlet air pressure was applied to the specimen and the air flow rate was measured under steady-state conditions.

The air flow, $Q$ ($m^3 s^{-1}$), obtained at environmental pressure, $P$, and temperature, $T$, was transformed to normal conditions of pressure, $P_0$, and temperature, $T_0$, in order to remove the effects of increasing kinematic viscosity and volume expansion of air with

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TABLE I Concrete dosage (kg m$^{-3}$), slump and porosity

| | Set | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Water/cement | 0.37 | 0.42 | 0.47 | 0.52 |
| Gravel (kg m$^{-3}$) | 372 | 372 | 372 | 372 |
| Stone (kg m$^{-3}$) | 842 | 842 | 842 | 842 |
| Sand (kg m$^{-3}$) | 628 | 628 | 628 | 628 |
| Cement (kg m$^{-3}$) | 434 | 382 | 340 | 307 |
| Water (kg m$^{-3}$) | 160 | 160 | 160 | 160 |
| Slump (mm) | 10 | 12 | 16 | 19 |
| Porosity (%) | 11.3 | 11.0 | 11.0 | 12.6 |

temperature rise

$$Q_0 = Q\frac{T_0}{P_0}\frac{P}{T} \tag{1}$$

The air permeability coefficient, $D_{\text{air}}$(m$^2$), was calculated from the Hagen–Poiseuille equation for a laminar flow of a compressible fluid through a network of small capillary pores under steady-state conditions

$$D_{\text{air}} = \frac{2QP_0L\eta}{A(P^2 - P_a^2)} \tag{2}$$

The air dynamic viscosity at 20 °C, $\eta$, is $1.8 \times 10^{-5}$ N s m$^{-2}$. The inlet pressures in the test, $P$, were 128 040, 154 715, 181 390 and 208 065 N m$^{-2}$, and the outlet and measuring pressures, $P_a$ and $P_0$, respectively, were 101.325 N m$^{-2}$. The specimen thickness, $L$ was 0.07 m and the passing surface, $A$, was 0.005 m$^2$.

## 3. Results

Fig. 1 shows the mean value of the air permeability coefficient of concrete under the four testing inlet pressures as a function of the water–cement ratio. The air permeability coefficients were almost independent of the applied pressure and increased with the water–cement ratio and the preconditioning temperature. The main difference between the specimens preconditioned at low and high temperatures is that it is possible to appreciate a "plateau" in the range of water–cement ratios between 0.42 and 0.47 in the first case, whereas low-temperature preconditioned concretes exhibit $D_{\text{air}}$ increasing almost linearly with the water–cement ratio.

The coefficient of variation corresponding to six samples tested for each variable studied, is given in Fig. 2. It is noticeable that the coefficient of variation is similar for each applied pressure. However, the variability is quite large, because concrete has a heterogeneous microstructure. Thus, the coefficient of variation does not follow any simple relationship with the water–cement ratio. For instance, the largest variation coefficient (VC) was found in the specimens with a water–cement ratio of 0.42 and preconditioned at 20 °C (VC = 40%), whereas the least corresponded to a water-cement ratio of 0.52 and preconditioned at 80 °C (VC = 10%). Summing up, it has been observed that the coefficient of permeability can exhibit a large coefficient of variation in practice [10].

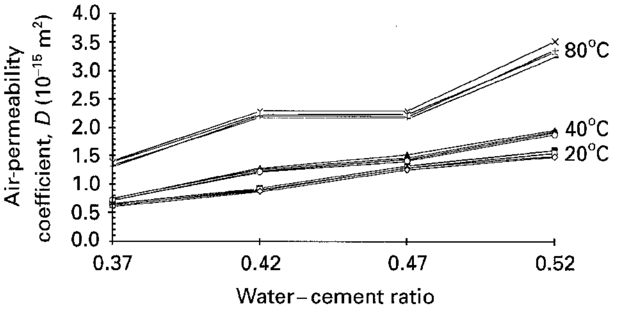

*Figure 1* Air-permeability coefficient versus water–cement ratio.

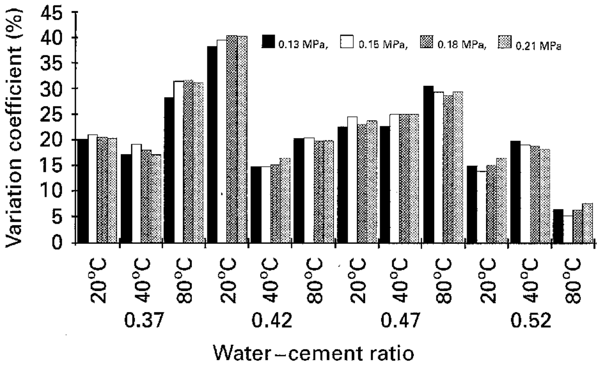

*Figure 2* Coefficient of variation of $D_{\text{air}}$ data (%).

Fig. 3 shows the relationship between the air flow rate and the pressure difference, $P^2 - P_a^2$. The good accuracy of the results is shown by means of the straight lines plotted in this graph. The calculated permeability coefficient, $D_{\text{calc}}$, obtained from the slope of this straight line, when multiplied by $2P_0L\eta$, is given in Fig. 4, where the correlation of the best fit, $r^2$, is higher than 0.99 in all cases, again demonstrating the good accuracy of the results.

In fact, the intercept of these lines should be zero according to Equation 2. However, low pressure data sometimes do not follow the assumption of laminar flow. In order to check this point, the straight lines were forced to cross the origin of the coordinates (0, 0). Fig. 5 shows almost identical values obtained in both cases, which indicates a good approximation to the assumed laminar flow. Finally, in this figure, a good agreement has been observed between the experimental and calculated air permeability coefficients.

## 4. Discussion

The effect of the water–cement ratio on the air permeability of cement pastes, mortars and concretes reflects a clear increase in this property, especially in specimens preconditioned at higher temperatures, as a consequence of the larger amount of pores having a low content of pore solution in addition to the possibility of microcracking [11]. In contrast, a "plateau" of $D_{\text{air}}$ has been observed in these specimens made with water–cement ratios of 0.42 and 0.47, and precured at 80 °C. Assuming a linear evolution of $D_{\text{air}}$

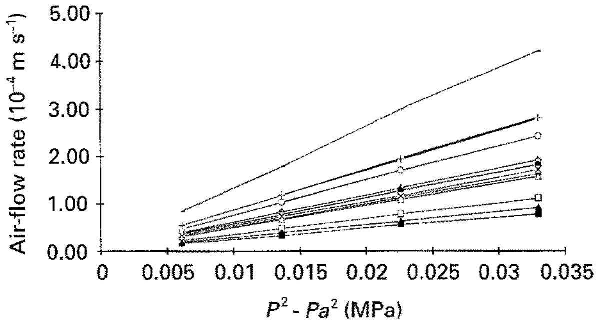

*Figure 3* Relationship between the air-flow rate and the applied pressure ratio $P^2$-$Pa^2$. Water : cement; (■), (▲), ( × ), 0.37; (□), (△), (∗), 0.42; (◆), (●), ( + ), 0.47; (◇), (○), ( – ), 0.52. Temperature; (■), (□), (◆), (◇), 20 °C; (▲), (△), (●), (○), 40 °C; ( × ), (∗), ( + ), ( – ), 80 °C.

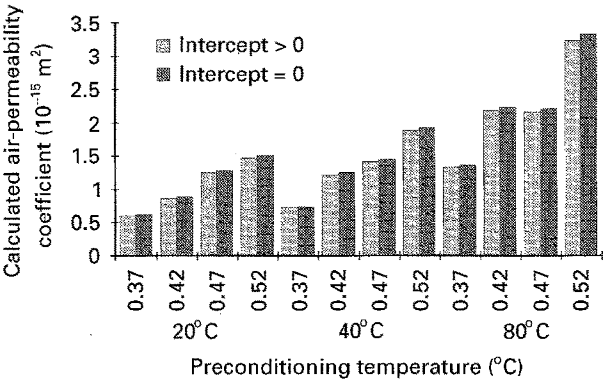

*Figure 4* Calculated air-permeability coefficient, $D_{\text{calc}}$, obtained from the slope of Fig. 3.

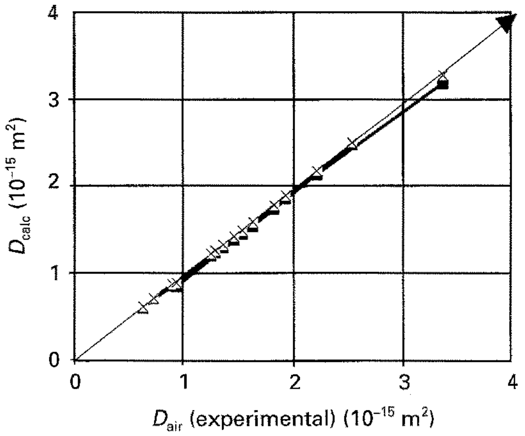

*Figure 5* Comparison between (——) the actual air-permeability coefficient, $D_{\text{air}}$ and the calculated air-permeability coefficient, $D_{\text{calc}}$: (—■—) $D_{\text{calc}}$ (intercept $> 0$); ( × ) $D_{\text{calc}}$ (intercept $= 0$).

with the water–cement ratio, the value of the specimen with a water–cement ratio of 0.42 and preconditioned at 80 °C seems to be higher than that expected. This fact may be a consequence of microcrack formation as a result of stresses induced by drying shrinkage. Nevertheless, it is also convenient to take into account the large variation coefficients found which ranged from 5 %–40 %, that is for most cases it may not be convenient to attribute that $D_{\text{air}}$ "plateau" to the possible presence of microcracks alone.

On the other hand, a variation coefficient of 25% in concrete air-permeability tests can be considered to be common value found in laboratory concrete specimens [10]. However, it is necessary to take into account that these data correspond to laboratory specimens and larger errors should be expected in real concrete structures [9].

In relation to the testing pressures, no appreciable effect on $D_{\text{air}}$ has been detected. This suggests that it is unnecessary to test the specimens at different pressures. Only sufficiently high testing pressure may give reliable air-permeability coefficients.

With regard to the air-permeability coefficient calculated from the slope of the lines plotted in Fig. 3, a good agreement can be observed between the calculated values and the experimental ones (Fig. 5). In spite of the good correlation found, the values obtained from the slope of Fig. 3 were forced to cross the origin of the coordinates, giving almost the same values as those obtained when best-fitted simply to a straight line (Fig. 4).

## 5. Conclusion

It has been found that the water–cement ratio is one of the key factors affecting concrete permeability, that is, small variations in this ratio promote large permeability changes. The air permeability increases with the water–cement ratio and with high preconditioning temperature, whereas at each of the four testing pressures this coefficient is similar, and hence, it is recommended that the test is performed only at one sufficiently high pressure.

In general, large differences in air-permeability coefficients have been obtained when similar samples were tested. However, the average coefficient of variation found, about 25%, is considered acceptable for concrete. Thus, it can be said that the air permeability test method for concrete gives reliable results. In contrast, the effects of cracking and defects which exist in the real structures, cannot be evaluated in laboratory specimens. Therefore, it is necessary to interpret the laboratory tests with caution.

## Acknowledgements

The authors are very grateful to all the people from ICCET who helped in this study.

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*Received 8 August*
*and accepted 15 December 1995*